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NEW NEUTRON PHYSICS USING SPALLATION SOURCES

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ABSTRACT: The extraordinary neutron intensities available from the new spallation pulsed neutron sources open up exciting opportunities for basic and applied research in neutron nuclear physics. The energy range of neutron research which is being explored with these sources extends from thermal energies to almost 800 MeV. The emphasis here is on prospective experiments below 100 keV neutron energy using the intense neutron bursts produced by the Proton Storage Ring (PSR) at Los Alamos.

Introduction

The purpose of this talk is to point out new opportunities for research in this field associated with powerful new spallation neutron sources operational at the National Laboratory for High Energy Physics in Japan, the Rutherford-Appleton Laboratory in the United Kingdom, and the Argonne National Laboratory and the Los Alamos National Laboratory in the United States. These sources have arrived primarily because of their extraordinary promise for condensed matter physics studies. Use of spallation sources by nuclear physicists has been modest up to now except at Los Alamos, but hopefully this talk will stimulate more neutron nuclear research to the benefit of both the condensed matter and neutron nuclear physics communities.

Spallation Neutron Sources

Condensed matter research using pulsed neutrons can be effectively conducted using a spallation neutron source with proton energy near one GeV and a proton pulse width of a few tenths of a microsecond. The burst is produced in two stages. First protons are accelerated in an r. f. linac to an energy of at least 100 MeV. This beam is accumulated in a ring, where it may be further accelerated, and then dumped in one circuit of the ring into a heavy metal target. Approximately 25 neutrons are produced per proton in the spallation process.

This concept is implemented[1] at Los Alamos in the Los Alamos Neutron Scattering Center (LANSCE) as shown in Fig. 1 by injecting 10% of the 800 MeV macropulses from LAMPF into the Proton Storage Ring (PSR)[2]. An average current on Target 1 of 100 microamperes is achieved by ejecting 0.27-microsecond wide pulses from the PSR containing 5 X 10^{13} protons at the rate of 12 Hertz. The resulting neutron intensity is about 10^{15} neutrons per pulse, or an average neutron intensity of 10^{16} neutrons per second. The instantaneous neutron production rate is 4 X 10^{21} per second. This mode provides intense beams for neutron physics research in the .01 to 100,000 eV range. For LANSCE operation at 100 microamperes we use the moderated neutron intensity formula

$$\text{Intensity} = 4 \times 10^{10}/EL^2 \text{ neutrons per eV per second}$$

for a 100-cm^2 sample at the neutron energy E (eV) with a flight path length of L (meters).

Intense bursts of MeV neutrons also can be produced using the same facility. Most of the time LAMPF provides 800 MeV proton beam for meson production. However it is also possible simultaneously with meson production to accelerate a smaller current of H^- beam at a point on some of the r. f. cycles 180 degrees in phase away from that used for H^+ acceleration. The two beams of different charge are separated at the end of the accelerator in a magnetic field. The H^- beam bypasses the storage ring and strikes a second spallation target, Target 4. The typical r. f. burst of about 300 picoseconds width is especially useful for research in the 100 keV to 800 MeV range. The average proton current for this mode is a few microamperes achieved at a pulse rate of about 35,000 Hz. This new capability and the planned research is described in detail by Wender[3] et. al. Multiplexing in the beam transport system of Line D and appropriate neutron shielding allows simultaneous neutron research at Targets 1 and 4. Altogether eight flight paths have been instrumented for research at the two targets with a few more to follow. Currently the research program is coordinated by eight staff members within the P-3 Group at Los Alamos with substantial participation by twelve other Los Alamos staff members.

Participation by outside laboratories and universities is being encouraged by Los Alamos and the Department of Energy and is already extensive. Institutions participating in neutron research at Los Alamos this year include KEK-Japan, Kyoto University, TRIUMF-Canada, University of Technology-Delft, University of Uppsala-Sweden, GKSS Research Center-FRG, Nuclear Research Center Julich-FRG, Hanover University-FRG, CEA-Grenoble, NBS, LLNL, ORNL, Harvard University, Princeton University, Duke University, North Carolina State University, Ohio University, University of Colorado, and University of California-Davis, University of California-Los Angeles, and the University of New Mexico. A list of titles of proposals for nuclear physics research in 1988 at Targets 1 and 4 are given in Table 1.

Table 1. Proposals for Nuclear Research in 1988 at Targets 1 and 4.

Neutron Induced Cross Sections on Radioactive Samples.

Differential Cross Sections for (p,xn) Reactions at 800 MeV.

Fundamental Symmetry Experiments Using Resonance Neutrons.

Electric Polarizability of the Neutron using eV Neutrons

Continuum Excitation by the (p,n) Reaction at 800 MeV.

Gamma Ray Production Measurements by keV and MeV Neutrons.

Neutron-Induced Fission Cross Sections from 1 to 400 MeV.

Neutron Physics and Charge Exchange Reactions.

Neutron-Induced Pion and Photon Production from Nuclei.

Giant Resonance Studies Using Neutron Capture Gamma Rays.

Neutron-induced Photon Emission.

Neutron-Proton Bremsstrahlung.

^{235}U Fission Cross Section from 1 to 200 MeV.

Response of BGO to Neutrons between 1 and 200 Mev.

Nuclear Level Density through (n,p) and (n,alpha) Reactions.

Benchmark Neutron Transport Experiments.

This paper will emphasize the prospects for experiments in the thermal to 10 keV range. Much of this work requires the use of polarized beams; before discussing the science it is therefore worthwhile to describe a new technique shown in Fig. 2 which we have used for obtaining polarized neutron beams at LANSCE based on polarized ^3He. The helium is polarized by bathing a mixture of helium gas and a small amount of vaporized rubidium with polarized laser light[4]. The alkali vapor is polarized in the optical pumping process and the polarization transferred to the helium nuclei by the spin-spin interaction. We have achieved a high ^3He polarization in a 10 atmosphere-cm^3 volume. The area of the cell was 0.75 cm^2, a length of 4 cm, and a pressure of 3.3 atmospheres. It was located at a flight path distance of 7 meters.

This technique has the advantage over a polarized hydrogen target[5] of little loss in neutron intensity in the polarization process, easy neutron spin flipping by flipping the ^3He by adiabatic fast passage, eight-hour polarization decay time, no cryogenics, and no strong magnetic field. It has the disadvantage that at its present stage the beam area is small and useful polarization experiments are limited to the energy range below 3 eV. Progress in the size of the polarized ^3He has moved rapidly and depends primarily on a better understanding of wall depolarization effects and on increasing the laser power. The laser light intensity on the cell was about 0.5 watts from a dye laser. If diode lasers could be implemented, the power might increase to the kilowatt level with orders of magnitude increase in the amount of polarized ^3He. We are also studying the possibility of a polarized ^3He detector which would offer interesting advantages for polarized neutron research.

In the interim we are installing for 1988 a polarized hydrogen target with beam area of 10 cm^2 which should provide by transmission a neutron polarization of about 60% with a loss of intensity of about five.

Parity Violation

The current most active field of neutron research requiring eV polarized beams is the study of enhanced parity violation in low energy p-wave resonances pioneered by the Dubna group[6]. They studied the transmission of neutron beams polarized along and against the neutron propagation vector k. Since the dot product $\sigma . k$ does not conserve parity, parity violation will be manifested as a difference in the two transmissions in the resonance. The largest effect observed to date[6] is a 7.3 ± 0.5 % parity mixing in the 0.734 eV resonance in ^{139}La. The KEK group has repeated the experiment[7] in the transmission mode and also by detecting the resonance capture gamma rays obtaining 10.4 ± 0.3 % by both methods establishing a clear discrepancy. Since the neutron width is very small compared to the capture width, the capture and transmission experiments are equivalent if the gamma detector efficiency is isotropic and the detector is centered on the sample.

This experiment was performed in a third way at Los Alamos[8] at LANSCE without neutron beam polarization apparatus as shown in Fig. 3. An unpolarized neutron beam striking a thick ^{139}La sample will emerge with polarization if P-violation is present in the resonance. We detect this polarization by passing the neutrons next through a spin flipper and then through a second sample of ^{139}La. A difference in the transmission for the two spin directions indicates the presence of P-violation[9]. Our value of 9.2 ± 1.7% was not sufficiently accurate to resolve the discrepancy between the Dubna and KEK experiments.

P-violation is a manifestation of the mixing via the weak force of the amplitude of an s-wave resonance into a neighboring p-wave resonance of the same spin[9]. Resonance capture gamma ray spectroscopy can play a role in two ways in assuring the proper conditions for interpreting the absence or presence of a P-violating effect. First it can be used to determine the spin of the p-wave resonance in accordance with established techniques. This is important since not all p-wave resonances have the proper spin to interfere with s-wave resonances. Second for non zero spin target nuclei, a p-wave resonance will be a mixture of two channel spins I ± 1/2. Only the I-1/2 amplitude can mix with the s-wave resonance. To extract an accurate matrix element for the parity mixing, the channel spin mixture must be determined. This mixture in the p-wave resonance can be determined by measuring the angular and polarization correlations in the capture gamma ray spectrum between states of known spin[10].

The measurements of P-violation in resonances has been carried out mostly with modest intensity neutron sources achieving a sensitivity of about 1 in 1000. The powerful spallation sources should allow sensitivities better by a factor of 100. It might therefore be possible to extend the measurement into the higher energy ranges where the sensitivity to parity mixing is reduced allowing the measurement of matrix elements for several resonances in a single nucleus. In this way an average matrix element for the nucleus analogous to a neutron strength function can be determined. If this could be done for many nuclei across a wide mass range, the mass dependence of a parity-mixing strength function could be measured.

Remembering that parity mixing is a property of the weak force, such a study would be of great interest since it would be the first measurement of the manifestation of the weak force in many nucleon systems. To fully appreciate this point it is useful to be reminded that both the strong and the weak force are well characterized at the nucleon-nucleon level. For the strong force this knowledge does not allow one to predict the properties of many nucleon systems. Perhaps the most fundamental manifestation of the strong force first predicted and measured was the giant resonances structure in the s-wave strength function. By analogy the measurement of the average value for the P-violating matrix element for many nuclei would allow the first measurement of the manifestation of the weak force in nuclei. Presently no predictions of the trend with A for this weak interaction strength function exist. Finally it should be mentioned that the channel spin mixture need not be measured for zero-spin targets. The derivation of an accurate matrix element from the observed parity mixing is therefore greatly simplified for this class of nuclei.

Current Mode Neutron Detection

The symmetry experiments may require statistical accuracy approaching 10^{-6} which is practical in view of the high intensity of the spallation sources. To achieve this in a ten-day run requires the detection of 10^{6} events per second in a single resonance. The low pulse rate and rather short flight path and therefore narrow time band imply instantaneous data collection rates as high as 10^{9} per second. Even if it were possible to detect individual events at the required rate, the problem of pile-up can have serious consequences. The pile-up rate will depend on the counting rate and the pile-up fraction will therefore vary across a resonance for example reaching a minimum at the bottom of a resonance transmission dip. If the neutron rate is somewhat different for the two helicities, a false difference in transmission will be observed.

We have therefore developed current mode neutron detection for the experiment using ^{6}Li-loaded glass on a photomultiplier. Care is taken in powering the tube dynode string to avoid dynode voltage shifts. The current transient from the tube generated by each PSR pulse is measured by an 8096 channel transient digitizer and the result added in a 8096 channel summing memory. This technique was first applied to high statistical accuracy transmission measurements to search for weak p-wave resonances in the rare earths. Fig. 4 shows results directly taken from the computer screen for ^{165}Ho. The data curve was collected in 0.3 seconds! A single PSR pulse examined on an oscilloscope screen looks almost the same. Measurements on about fifteen isotopes were completed in one 36-hour running period. The technique has the disadvantage that a bias level cannot be set and pulse shape discrimination is not possible. The ability to collect data at exceptionally high rates without pile-up is however crucial to the fundamental symmetry experiments.

T-Violation in the Weak Force

Although CP-violation was detected long ago in neutral kaon decay[11], time reversal invariance violation (T-violation) implied by CPT conservation (C- charge conjugation, P-parity operation, T-time reversal operation) has never been directly detected. Nor has CP- or T- violation been seen in any other system. The lack of understanding of the nature of CP-violation is a major barrier to further advances in the Standard Model. The most sensitive and extensive search to date has been for detection of an electric dipole moment of the neutron which would be an unambiguous signature for T-violation in the neutron.

The presence of P-violation in neutron resonances is a signature for the weak force. Such resonances are therefore alternative candidate nuclear systems for a sensitive search for T-violation. The T-violation will be manifested in an amplitude containing a term of the form ($\sigma \cdot k \times I$) where σ is the neutron spin, I the spin of the target nucleus, and k the neutron momentum vector. The experiment requires the polarization of the neutron beam and the target nucleus normal to one another and also both normal to k. T-violation would be manifested as a change in the transmission at resonance when the neutron spin direction is changed by 180 degrees. The experiment is significantly complicated by the existence of pseudo-magnetic rotation[12].

It appears that the spallation sources might give a statistical accuracy for detecting a difference in the transmission of the two polarizations at resonance of 10^{-6}.

For a resonance exhibiting P- violation (weak force fraction) of 10^{-1}, a T- violation sensitivity of 10^{-5} might be obtained[13]. According to Herczeg[14], sensitivity in the range of 10^{-3} and below is useful for testing various proposed extensions of the standard model.

T-Violation in the Strong Force

T-violation has never been observed in the strong force. By measurements of the cross sections for reciprocal reactions such as (p,α) and (α,p) and other means, the sensitivity limit is at the one part in 1000 level[15]. Apparently a much more stringent limit could be placed by resonance transmission of polarized neutrons on an aligned target arranged at a 45 degree angle to the neutron beam[16]. A vector product of interest for T-violation in the strong force is ($\sigma \cdot k \times I$) ($k \cdot I$). A statistical accuracy for this experiment of 10^{-6} would allow one to extend the sensitivity for T-violation in the strong force by three orders of magnitude. Bunakov[17] reports there is resonance enhancement of three to five orders of magnitude in the resonance experiments on T-violation. The resulting true sensitivity of 10^{-9-11} would be in the range to test current theory.

Laser Control of Nuclear Reactors

The polarized ^3He cell described above offers a surprising opportunity for controlling a reactor by means of a laser. Consider a 1-cm diameter tube at the center of a bare homogeneous thermal reactor with both height and diameter of 1 meter. If this tube contains ^3He at a pressure of 3 X 10^{20} atoms/cm^3, nearly all neutrons entering would be absorbed in the ^3He and the reactor reactivity would be depressed by about 6 %. However if the ^3He were 100 % polarized by laser light in the up direction, the absorption cross section for the spin down neutrons would double but the cross section for the spin up neutrons would go to zero. The spin down neutrons would continue to be fully absorbed. However the spin up neutrons would not be absorbed at all. Therefore the reactivity would increase by 3 % allowing a 3 % range of reactivity control. (A reactor with 1 % excess reactivity is essentially out of control.) The polarization could be destroyed instantaneously (and the reactivity reduced by 3 %) by a pulsed magnetic field arising from a current pulse through a coil wrapped around the cylinder.

Five such tubes arranged in a circle of about 25-cm radius each containing only 10 times the amount of gas polarized in the above P-violation experiments would provide 3 % reactivity control. It appears that polarization of this much ^{3}He should be possible soon using diode lasers. An incidental result of this means of control is that the neutron flux in the reactor would be partially polarized upward.

Unstable Nuclei

The very high intensity combined with the very low duty cycle available at LANSCE make possible measurements on very small masses of radioactive nuclei. Two experiments are planned which are of strong interest for astrophysics. The first is the study of positron emitters which generally have a positive Q for the (n,p) process. The neutron beam is collimated at a flight path of 5.5 meters to a 4 mm umbra. The sample is a 2 mm spot on a thin aluminum foil. Protons from the (n,p) reaction are detected by a surface barrier detector placed outside of the neutron beam. The neutron flux is monitored by a thin layer of ^{6}Li.

Measurements on samples of ^{7}Be, ^{22}Na, ^{35}Cl, ^{56}Co, and ^{57}Co are completed or underway. The first results were obtained in a few days using a 90 nanogram sample of 53-day ^{7}Be in the thermal to 20 keV range[18]. The ^{7}Be data may be applied to the calculation of the primordial nucleosynthesis of ^{7}Li in the standard hot big-bang model[17].

The second experiment on unstable nuclei is the measurement of capture cross sections from thermal to about 30 keV. A 30-cm cube of BaF will be used with a high bias to detect the summed capture gamma rays in the presence of a high singles rate from the decay of the sample. It appears that measurements of eV resonance capture will be practical for nuclei with half lives as short as 5 days; capture at 30 keV should be practical for half-lives as short as 100 days. It is surprising to find that measurements might be practical on as many as 190 unstable nuclides. Our experiments on unstable nuclei are discussed in more detail in this meeting by Koehler.

Neutron Capture Gamma Ray Spectroscopy

It is well known that resonances of neutron cross sections can exhibit features in their capture gamma ray spectra atypical of the statistical picture expected from the compound nucleus concept. The best established of these is a mechanism that is described as a valency neutron transition[19] and is closely related to the direct capture process[20] found to be predominate in the thermal cross sections of many light nuclides. However the understanding of these processes is poor at present and data in the resonance region is not easily measured. Probably a great deal could be learned if the measurements could be made more quickly and on smaller samples with satisfactory background and resolution conditions.

The source intensity available from a spallation source such as LANSCE exceeds[21] that from the best linacs where these experiments are operational by a factor of 100. This advantage might be substantially greater when due account is taken of the inefficient neutron moderator geometry required at electron linacs to reduce the gamma flash to an acceptable level. In addition there is no gamma flash to degrade the data taken at higher neutron energies. However it is not clear that these advantages put the spallation sources on top for this type of experiment. The linacs have a shorter pulse by a factor of about 25 which allows measurements of a given neutron energy resolution at a shorter flight path. Furthermore the higher repetition rate is generally advantageous from duty cycle arguments.

It is therefore inappropriate to claim that the spallation source will obviously be better than the electron linac for resonance gamma ray spectroscopy. However the present rate of progress in this field is definitely limited by the difficulty of doing these measurements with the sources presently employed. It would be very desirable to evaluate the effectiveness of the spallation source for this work by actual experiments.

Ultrahigh Resolution Photonuclear Research

The study of individual compound nuclear states in heavy nuclei using gamma-rays is difficult since a monochromatic and variable energy source with the necessary resolution is not available. Some useful work has been possible for lighter nuclei using the threshold photoneutron technique[22] and gamma-rays produced via the (p,gamma) reaction. However general studies require a resolution of a few eV. Useful intensities for energies of about 7 Mev might be obtained by neutron capture on nuclei with strong transitions to the ground or other low lying states.

Consider the placement of a sample of ^{56}Fe at a flight path distance of 50 meters viewing the moderator on a spallation source. This nucleus exhibits a strong ground state gamma-ray for thermal neutron capture. The thermal capture cross section is 2.59 barns. This cross section behaves approximately as a 1/V cross section so that some of strong gamma-rays will be produced for neutrons well into the eV range. The energy of the ground state transition will be $E = E_B + E_n$ where E_B is the binding energy and E_n is the neutron energy. The energy of the gamma-ray therefore will be directly correlated with the energy of the neutron. By placing a sample and an appropriate detector for photonuclear reactions near the gamma-ray source, it might be possible to do ultrahigh resolution photonuclear spectroscopy.

Several factors govern the resolution for this proposed concept; however the most important is the Doppler broadening of the gamma-ray in the emission process. This is about 5 eV for a room temperature mass 100 emitter with an energy of 7 MeV. The resolution in the neutron also contributes. Fig. 5 shows the resolution as a function of neutron capture energy when the approximately constant emission doppler effect is combined with the neutron energy resolution for a flight path of 50 meters. Over much of the energy range the resolution is better than one part per million.

A calculation of the intensity is also shown in Fig. 5. The calculation assumes that a PSR Proton current of 100 microamperes, a thermal capture cross section for the gamma-ray of one barn, a potential scattering cross section of 10 barns, an ^{56}Fe target thickness in which 10% of the neutrons interact, a flight path of 50 meters, a target area of 100 cm^2 and emission into a full sphere. The result of the calculation is expressed as the integral of the average number of gamma-rays produced per second from 10 eV up to a given higher energy for the conditions described above. For example 2800 photons per second will be produced in the energy range from 10 to 100 eV, which might allow useful experiments.

Possible experiments include photofission on non-thermal neutron fissioning isotopes achieved by detection of fission gamma-rays and/or fission neutrons, photon-induced gamma-ray emission by detecting at least two gamma-rays in a pair of detectors arranged in coincidence, MeV photoneutron emission, or perhaps photoproton emission. These experiments would be complicated by backgrounds from a high proportion of scattered eV energy neutrons. While the impact of this class of experiments is not clear at present, it appears that the intensities could make possible photonuclear experiments with a resolution better than 1 part in 1 million- perhaps the highest resolution nuclear physics experiment performed outside of the Mossbauer effect.

Benchmark Neutron Transport Experiments

The Los Alamos National Laboratory maintains high capability neutron transport codes for a variety of programs.
The testing of the performance of these codes for both the accuracy of the input data and the transport algorithms using critical assemblies is not entirely satisfactory as the critical assembly averages over all transport properties of a system to give only one number for calculation. A technique therefore was devised for LANSCE which can be readily simulated by computer which would provide a more stringent test of code performance.

A liquid scintillator 10-cm in diameter and 2.5-cm thick was mounted on a photomultiplier and placed in a 10-cm diameter collimated neutron beam at distance of about 60 meters from a moderator associated with the LANSCE pulsed neutron source. An assembly containing fissile material and other materials such as a CH_2 moderator is placed against the scintillator and in the neutron beam with only a layer of cadmium separating the assembly from the scintillator. For neutron energies below 1 keV the decay time of the assembly is short compared to the time-of-flight of neutrons to the assembly. Fission neutrons are recorded by the detector and gamma rays eliminated by pulse shape discrimination. The geometry of the experiment is reproduced in the code and the code performance compared with the experiment. Results from two experiments lasting about 8 hours each for thicknesses of about 5 and 25 gm/cm^2 of ^{235}U are shown in Fig. 7 in the energy range from 20 to 31 eV.

Here as in other energy ranges there are striking differences between the two thicknesses. The data are being compared with the best available resonance parameter characterization of ^{235}U. The capture-to-fission ratio must be accurately known to get a satisfactory fit to both thicknesses.

Neutron Pumped Gamma-Ray Laser

A gamma-ray laser would combine the special properties of incoherent x- and gamma-rays with the usual features of the laser. It would therefore possess the extraordinary qualities of penetration, ionizing ability, wavelength of interatomic spacing, interaction with electrons in inner shells of atoms, coherence, intensity, monochromaticity, directionality, reflectivity and focal properties. While the development and application of such a device would be interdisciplinary, almost certainly it would be driven by nuclear processes in the province of low energy nuclear physics. The community represented here probably will play the lead role of devising, building, and first using a gamma-ray laser.

The possibility of using neutron reactions to pump a gamma ray laser has been discouraged through apparently sound general arguments. They can be briefly summarized as requiring neutron intensities which probably can only be produced in a nuclear explosion which would deposit so much energy in the lasing medium that it would be vaporized before lasing could begin[23]. A concept will be described allowing neutron intensity reduction by several orders of magnitude which apparently enables operation at neutron intensities below the vaporization threshold.

Laser action must begin with a nuclear process giving rise to an inversion (more than half the nuclei in an excited state aside from statistical factors). The half-life of the excited state will probably be in the interval from 1 to 1000 nanoseconds. The macroscopic stimulated emission process must be greater than the macroscopic attenation processes in the laser medium. The stimulated emission cross section can be enhanced into the million barn range by establishing recoilless emission conditions. The attenuation can be greatly reduced by performing isotopic separation of the excited nuclei and subsequent implantation into a favorable host medium in a time short compared to the isomer half-life.

All this might be achieved by pumping the famous 14.4 keV Mossbauer transition in ^{57}Fe via the $^{57}Co(n,p)^{57}Fe$ reaction. The reaction leads to an inversion as shown in Fig. 8. Starting from the $7/2^-$ state of ^{57}Co an s-wave neutron can excite 3^- states in ^{58}Co. Angular momentum will restrict the emission of protons to the 136 keV excited state of ^{57}Fe. This state decays with $T_{1/2}$ of 8.6 nanoseconds to the 14.4 keV state 89% of the time creating the inversion.

The recoil from the 1.6 MeV proton emission kicks the ^{57}Fe with an energy of about 25 keV and it will travel about 100 A in the ^{57}Co. If the ^{57}Co is distributed in a layer of about this thickness, the ^{57}Fe nucleus will be knocked free and it can be stopped in a second layer of low gamma attenuation and good Mossbauer binding properties such as beryllium or powdered diamond. The range of the ^{57}Fe in these materials is about 250 A. Fig. 9a and b show a spool of Be foil coated on one side with ^{57}Co. The laser action is parallel to the spool axis. The neutron intensity requirements for lasing are reduced by several thousand by the recoil-based isotopic separation and implantation. Calculations indicate that the gain per centimeter would be high enough to de-excite a substantial fraction of the nuclei in a single pass. The coherence and directionality of the emission however would be poor. These features may be much improved with the addition of mirrors.

Mirrors may be constructed using four single crystals in a diffraction mode arranged as shown in Fig. 9c. A high gain per centimeter would compensate for a low reflectivity which might be in the range of only 50% per crystal. Within the 100 nanosecond half-life, the light would travel about 30 meters allowing time for many circuits and thereby greatly improving the laser efficiency and the coherence and emittance of the beam.

The prospects for this system depends on the ^{57}Co(n,p) cross section in the eV and lower keV range. The most likely possibility is a resonance at about 400 eV with a peak (n,p) cross section of about 300 barns and a width of about 7 eV. Hopefully (n,p) measurements will be completed on this nucleus at LANSCE this fall. Measurements made at the OWR reactor in the thermal range give a cross section[24] twice as large as that expected if all of it were associated with the low energy wing of the proposed resonance. The density of excited nuclei required for this concept is reduced by six orders of magnitude below that required in ^{57}Fe without nuclear transmutation, isotopic separation, and implantation. In addition the expected size and position of the resonance are favorable for the inversion dynamics. At the reduced neutron intensity, the lasing medium should survive the pumping process. There may be many such pumping schemes which might be identified by spectroscopic studies on low lying states of promising nuclei. A laboratory source of coherent gamma rays would be a truly exciting development both for low energy nuclear physics and for many other research fields as well.

Neutron-induced Electronic Excitation

Electronic excitation in atoms and molecules via neutron-induced reactions can occur by three mechanisms. The first is the much discussed interaction of the magnetic moments of the neutron and the electron[25]. One is interested in eV incoming neutron energies and in electronic excitations of a few eV with small momentum transfer and excellent energy resolution (1/1000). The second[26] is excitation arising from recoil of the nucleus under the electron cloud in a high momentum transfer neutron-nucleus interaction. The third[26] is another high momentum transfer excitation arising from non-adiabatic coupling (NAC) between the nuclei in a diatomic or more complex molecule. Background could be significantly reduced by detecting the decay photon following electronic excitation in coincidence with the scattered neutron. For the NAC interaction, the selection rules are substantially different from electromagnetic selection rules and more restrictive so that the spectrum might be less complex and therefore more easily resolved and interpreted.

The first and third experiments are difficult since the measurement of incoming and outgoing neutron energy is required with high resolution for a white neutron spectrum. The second experiment appears to be practical and can be illustrated with counting rates for the measurement of the 1s3s to 1s2p 7281 A^o optical transition in helium.

The recoil given the He nucleus by the scattering neutron induces excitation to the 1snp group of excited states for about 1 % of the neutron collisions. Most of these will preferentially decay directly back to the 1s1s ground state with energies outside of the optical range. However about 2.5% of these will decay to the 1s3s level which subsequently can only decay to the 1s2p state. By use of a filter transmitting only photons close to the 7281 A^o line, background can be reduced by a factor of 1000 with little loss of signal. The photons would be detected by two photomultiplier tubes observing the light from a 10 atmosphere high pressure helium cell of 2.5 X 5 X 5 cm^3 volume. The neutron beam would be collimated to a 2.5 X 5 cm^2 area at a flight path of 30 meters. The estimated counting rate is about 2.5 events per second between 5 and 15 keV. The excitation probability increases linearly with the energy.

Resonance Neutron Optics

The wave properties of neutrons give rise to optical properties which are well established for thermal energies. These properties are usually expressed through an index of refraction $n = 1 - \lambda^2 \rho a_{coh}/2\pi$ where λ is the wavelength of the neutron, ρ is the density of nuclei, and a is the real component of the coherent neutron scattering length. For higher energy neutrons the strong wavelength dependence results in a value for n very close to unity except at resonances where the scattering length can become quite large compared to that at thermal energies- thereby compensating for the shorter wave length. At resonance it is probably possible to observe resonance total reflection and perhaps even neutron focusing with long focal length lenses. The large resonance scattering length also should allow enhanced diffraction effects at resonances which should be observable in powder and single crystal diffraction studies.

This experiment was tried[27] in 1987 at LANSCE at the 8.047 eV resonance in ^{152}Sm using a thin film of natural Sm plated onto a glass substrate as the low angle reflector.

The experiment was unsuccessful; however, there are a number of ways in which the experiment could be improved including using a separated isotope, selecting a more favorable resonance, improving the collimation, increasing the detector efficiency, and using the full neutron intensity available at LANSCE. Great care is required to observe this effect unambiguously.

Resonance Neutron Radiography

This technique[28] makes use of the strong neutron resonances in nuclei for nondestructive diagnostic purposes. Transmission measurements conducted using time-of-flight techniques allow the quantitative determination of the isotopic content of an object. The use of two-dimensional position-sensitive neutron detectors with resolution as good as 300 microns also allows a measurement of the position distribution of particular isotopes of interest. In some situations the technique might be enhanced by the application of gamma-ray spectroscopy. The new high intensity sources and high data collection techniques will enhance the effectiveness of this method.

Lead Slowing-down Spectrometer for Ultra-high Intensity

The lead slowing down spectrometer[29] is a means of creating a very high intensity source for poor resolution neutron spectrometry using the time correlation of the neutrons in a 1 m^3 lead assembly. The method is particularly applicable to very small quantities of very short lived nuclei. The PSR could inject 10^{15} n/burst into the assembly, which is probably five orders of magnitude more neutrons than other drivers provide. The average neutron intensity also is probably larger by a factor of 10^3. Since the sensitivity gain of this instrument is about 10^4 times that of a neutron time-of-flight experiment of comparable resolution, the sensitivity for cross section measurements would be extraordinary for experiments where poor resolution is acceptable. Experiments such as the fission cross section of the 26 minute isomer of ^{235}U might be practical by this method.

Neutron-neutron Scattering

The neutron-neutron scattering length has never been directly measured and its value to an accuracy of a few percent is of great interest. Experiments on the edge of practicality have been proposed for steady state thermal neutron sources. Since the n-n scattering length depends on the square of the neutron flux, a high intensity pulsed source has a decided advantage over the steady state reactor.

A cavity can be built containing a gas of thermal neutrons which is viewed by a detector through a collimated path which does not allow the detector to see the cavity walls. If the cavity is filled with a low density of hydrogen gas, the n-p scattering will be proportional to the first power of the flux. Therefore by measuring the scattering rate as a function of peak flux in the cavity, the n-n rate can be separated from the n-p rate and the n-n scattering length measured relative to the n-p scattering length. Although a calculation has not been done for a spallation source, it has been done for a pulsed reactor[30]. For a flux of 10^{17} n/cm^2-sec, a cavity 10 cm long and 10 cm in radius, a detector distance of 12 meters, a detector radius of 10 cm and a pulse width of 6 milliseconds, the detected rate is 30 neutrons per pulse.

Conclusions

The power of these sources for neutron nuclear physics is truly exciting for the lower energy range and complementary capabilities also can be readily implemented for forefront work in the MeV range. I urge the community represented here to become actively involved in physics at these sources. As an incentive I wish to remind you that neutron physics is always intensity limited. However the rate of advance in intensity is truly astounding as shown if Fig. 10. The intensity increase has been almost two orders of magnitude per decade for the past 35 years and there is no technological barrier against this continuing for some time. Neutron experiments which you considered and rejected years ago might now be easy.

We nuclear physicists should salute the neutron scattering community for their role in continuing the advance in source intensity, and we should work cooperatively to assure the full exploitation of all the science made accessible by these new facilities.

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Figure Captions

Fig. 1 The Los Alamos Epithermal and White Sources based at LAMPF. As described in the text, 10% of the LAMPF beam is directed to the Proton Storage Ring which compresses the beam into 0.27-microsecond pulses and feeds them to LANSCE (Target 1). A few microamperes of H^- beam is accelerated simultaneously on most LAMPF pulses along with the proton beam. These beams are separated at the end of the accelerator and bypass the PSR on the way to the MeV White Source (Target 4). Experiments can be conducted at Targets 1 and 4 simultaneously.

Fig. 2 Laser Polarization of a Neutron Beam. ^3He- rubidium vapor mixture in a glass cell is polarized using polarized laser light. A krypton ion laser is used to drive a dye laser which is tuned to a particular transition in the rubidium vapor. The polarization of the laser light produced by the quarter wave plate, polarizes the Rb atoms and this polarization is transmitted to the ^3He by collisions.

Fig. 3 Plan view of the Los Alamos P-violation experiment. Neutrons travel through seven meters of biological shielding and collimation to the first La_2O_3 sample. The beam transmitted through the sample is weakly longitudinally polarized near the 0.734 eV resonance. The beam then travels through three sets of coils, which make up the spin flipper, to the second sample and are detected in a ^6Li-loaded glass detector.

Fig. 4 The points show a transmission spectrum (inverted) taken in 0.3 seconds with the current mode detection system. The inset shows the detector with P. M. tube dynodes stabilized by four high current power supplies. The current is smoothed with an appropriate time constant and measured in a transient digitizer whose output is recorded in a summing memory.

Fig. 5 Intensity and resolution for ultrahigh resolution ($< 1/10^6$) photonuclear experiments using 7.646 MeV gamma-rays derived from variable energy eV neutron capture in ^{56}Fe. The left ordinate shows the integral of the number of gamma rays produced per second by neutrons with energies between 10 eV and a higher energy given on the abscissa. The ordinate on the right shows the resolution of the gamma-ray in eV.

Fig. 6. Reactor Control Using Laser-Polarized ^3He. A tube is filled with ^3He to a pressure sufficient to absorb most of the neutrons which enter it. The ^3He is next polarized as described in the text. One spin state is now transmitted whereas the macroscopic absorption cross section for the other doubles- increasing the reactivity. The flux profile in the reactor for the polarized and unpolarized ^3He is shown at the bottom.

Fig. 7 The fission neutron rate for thick and thin assemblies containing ^{235}U induced by neutrons in the 20 to 32 eV range.

Fig. 8 The $^{57}Co(n,p)^{57}Fe$ reaction producing a population inversion for the 14.4 keV gamma-ray in ^{57}Fe. For 1-0 neutrons only the 3^- states reached in ^{58}Co can decay with appreciable amplitude by proton emission to ^{57}Fe. Of the possible ^{57}Fe states only the 136 keV state can be reached by 1-0 protons. It decays 89% of the time to the 14.4 keV state producing the inversion.

Fig. 9 Geometry for the gamma-ray laser. A 0.005-cm thick Be foil is coated on both sides with a 100-A thick layer of ^{57}Co. A thin 250-A thick layer of Be is then deposited on the cobalt on one side. A cylinder is then wound as shown in a. The cross section across the cylinder is shown in b; stimulated emission is directed vertically. The four-mirror arrangement shown in c improves the emittance and the efficiency.

Fig. 10 The advance of spallation neutron source intensity for the production of epithermal neutrons. The intensity is the total neutron production averaged over one second.

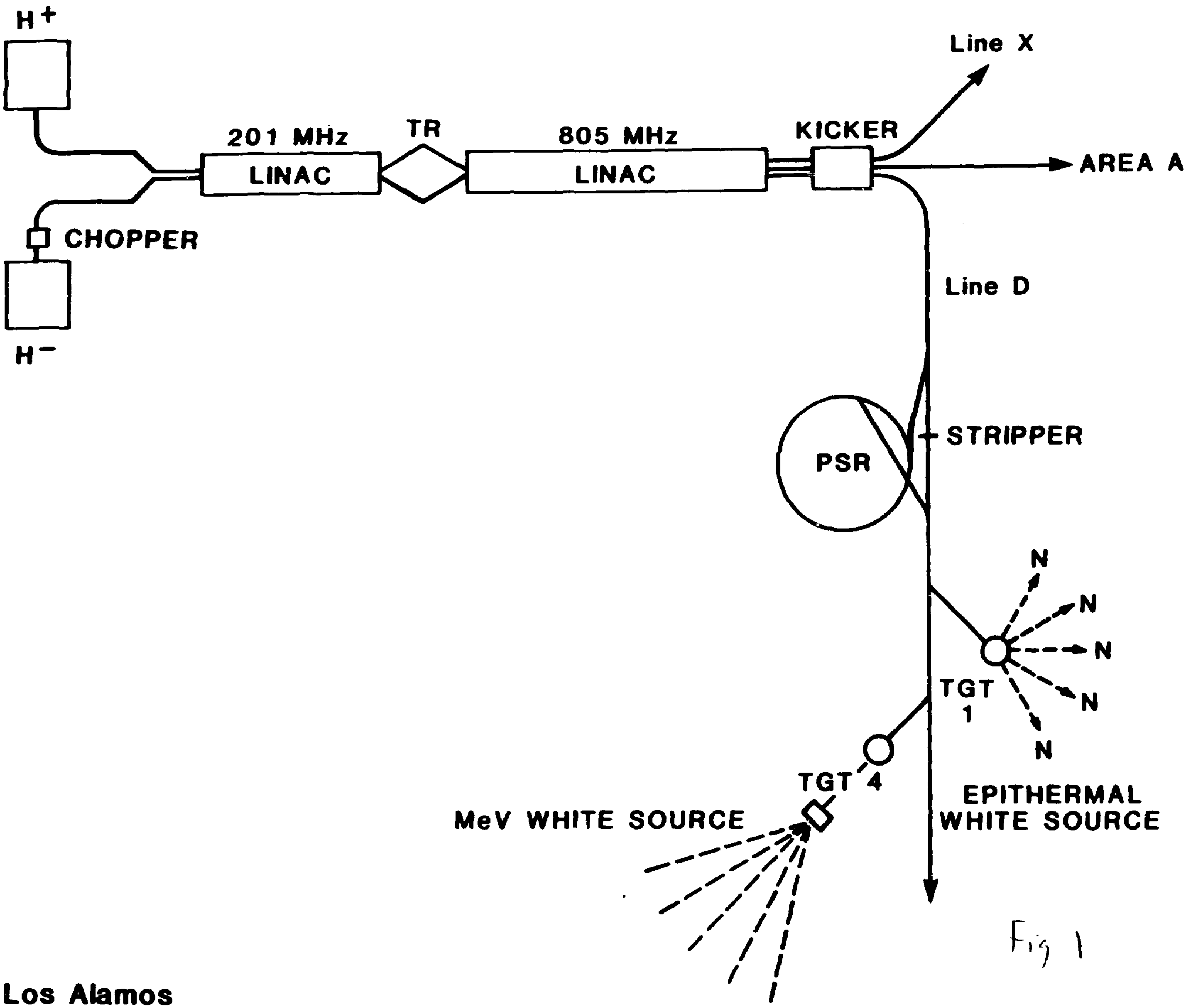
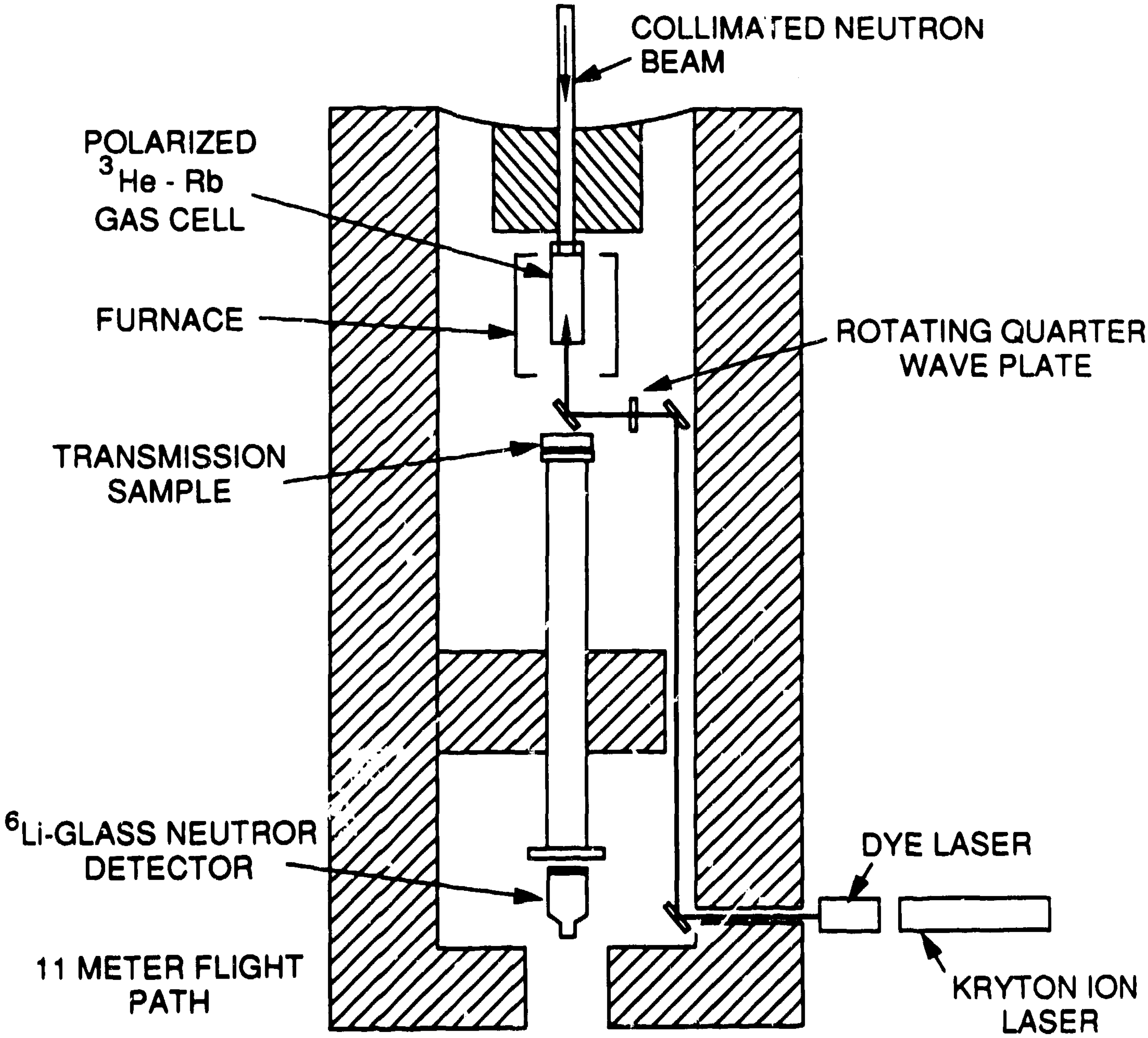
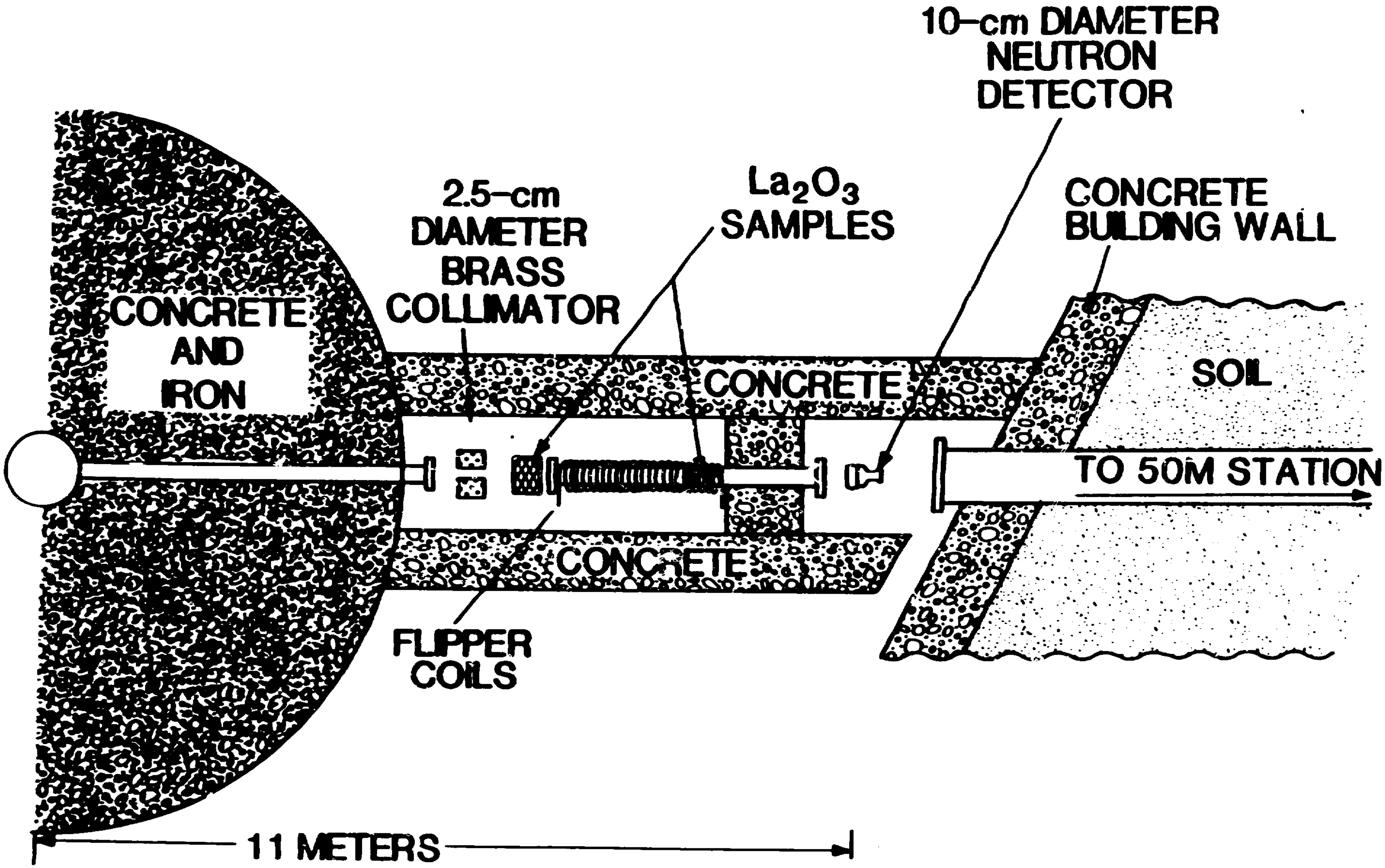


Fig 1

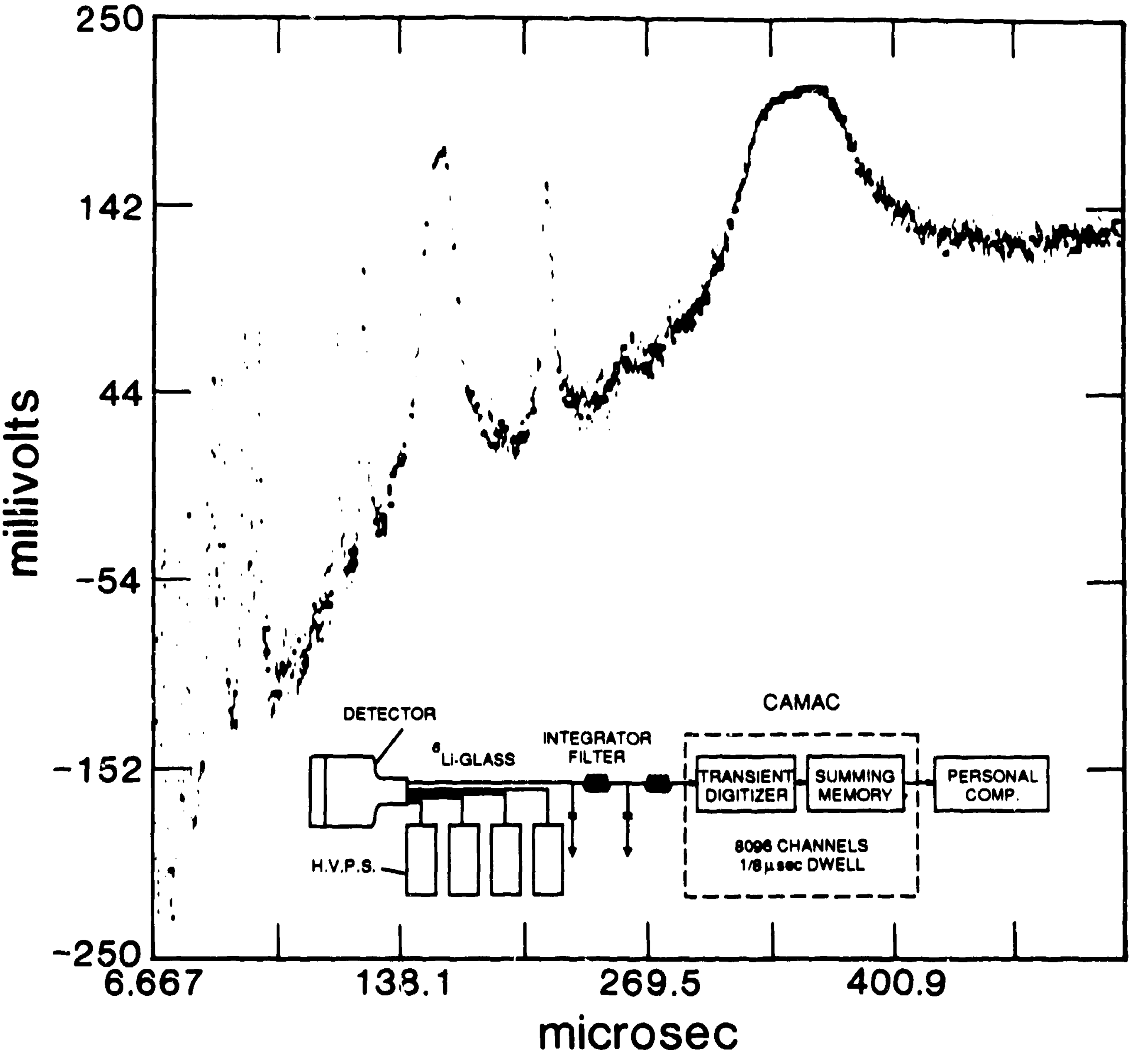
Los Alamos

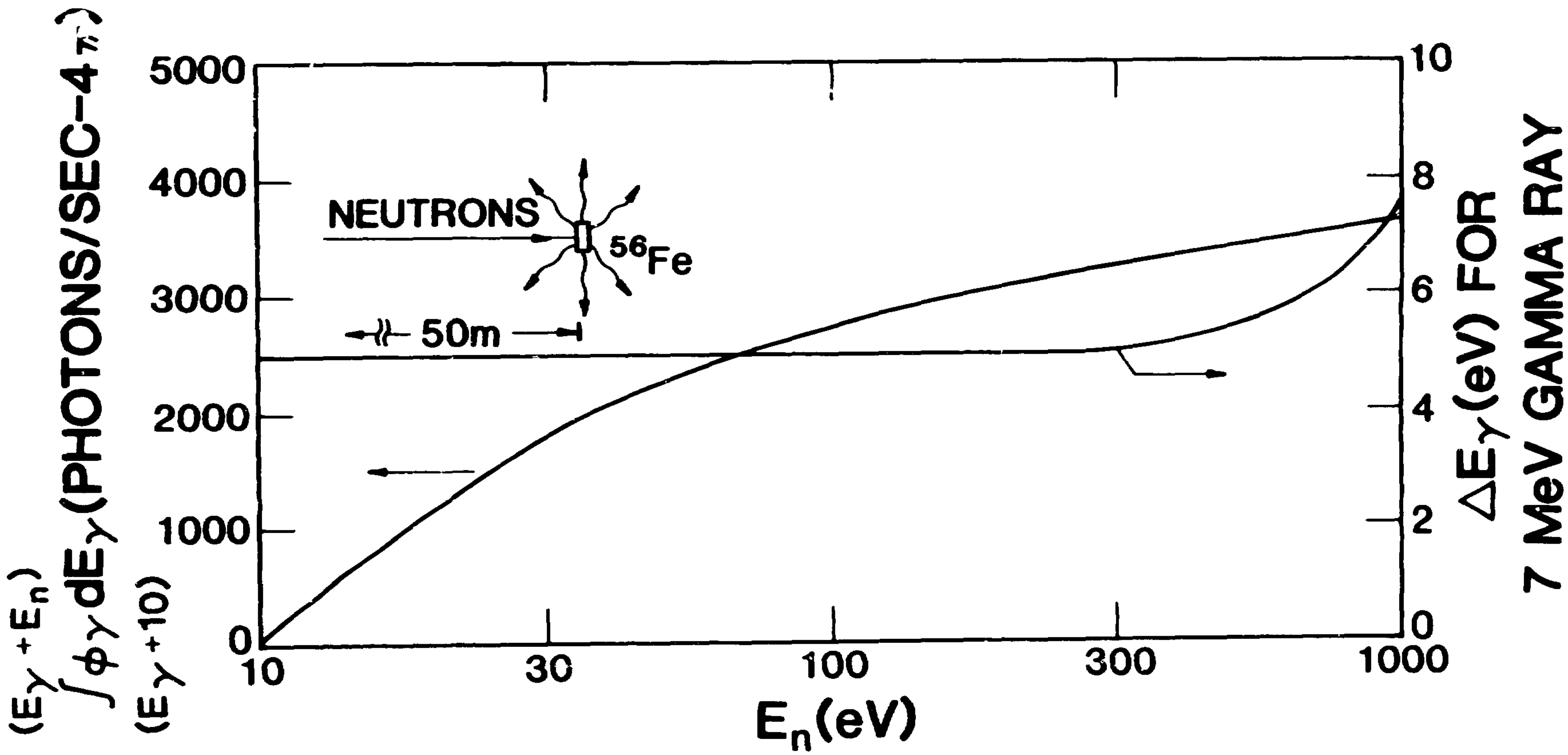

COLLIMATED NEUTRON
BEAM
POLARIZED
^{3}He - Rb
GAS CELL
FURNACE
ROTATING QUARTER
WAVE PLATE
TRANSMISSION
SAMPLE
^{6}Li-GLASS NEUTRON
DETECTOR
DYE LASER
11 METER FLIGHT
PATH
KRYTON ION
LASER

P-VIOLATION



10–cm DIAMETER
NEUTRON
DETECTOR
2.5–cm
DIAMETER
BRASS
COLLIMATOR
La_2O_3
SAMPLES
CONCRETE
BUILDING WALL
CONCRETE
AND
IRON
CONCRETE
SOIL
TO 50M STATION
CONCRETE
FLIPPER
COILS
11 METERS


250
142
44
-54
-152
-250
millivolts
6.667
138.1
269.5
400.9
microsec
CAMAC
DETECTOR
6LI-GLASS
INTEGRATOR
FILTER
TRANSIENT
DIGITIZER
SUMMING
MEMORY
PERSONAL
COMP.
H.V.P.S.
8096 CHANNELS
1/8 μsec DWELL



5000
4000
3000
2000
1000
0
10
30
100
300
1000
10
8
6
4
2
0
NEUTRONS
56Fe
50m
En(eV)
(Eγ+En) ∫ (Eγ+10) φγ dEγ (PHOTONS/SEC–4π)
ΔEγ(eV) FOR
7 MeV GAMMA RAY

Fig.

REACTOR CONTROL USING LASER POLARIZED ^{3}He

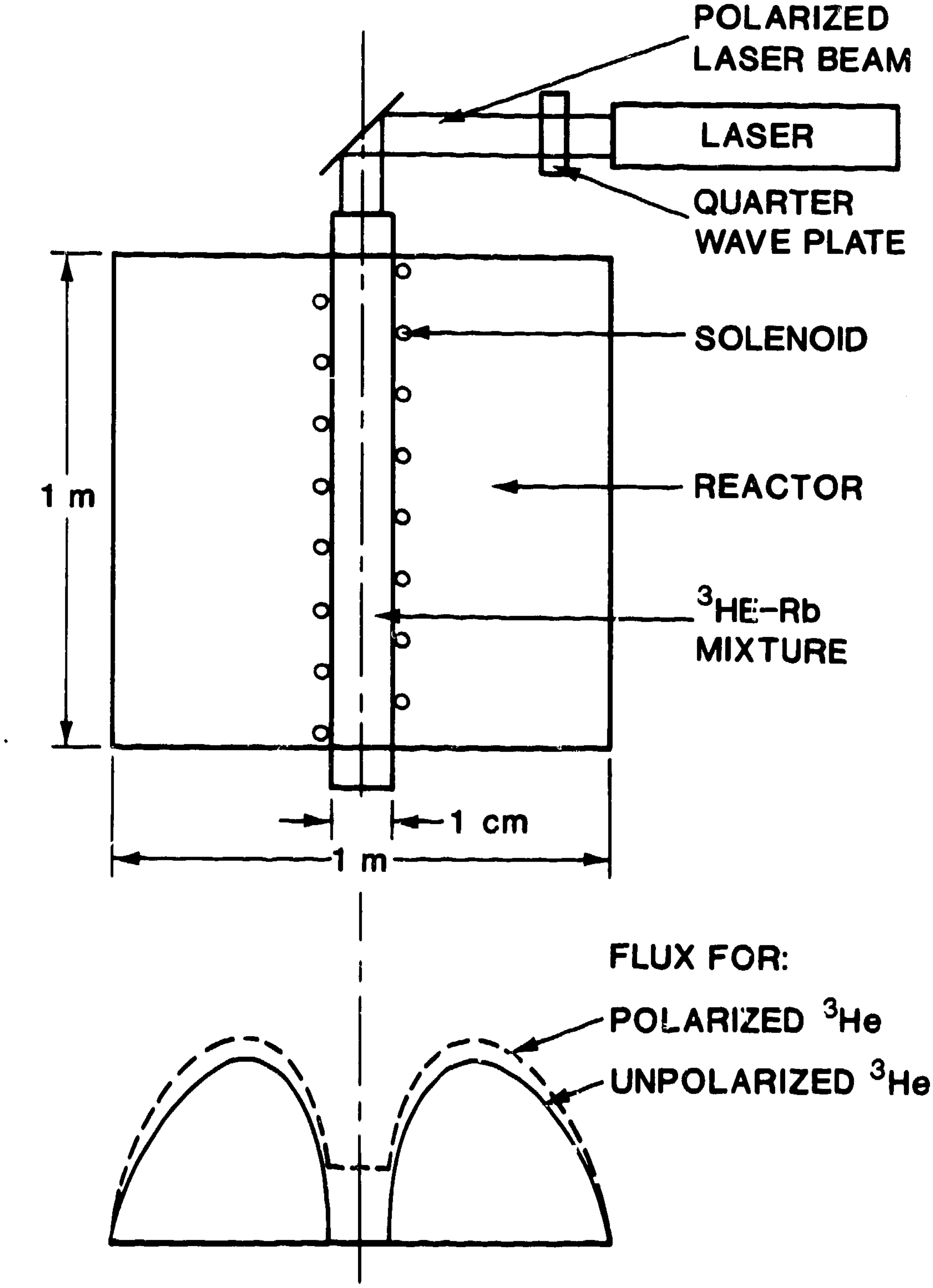
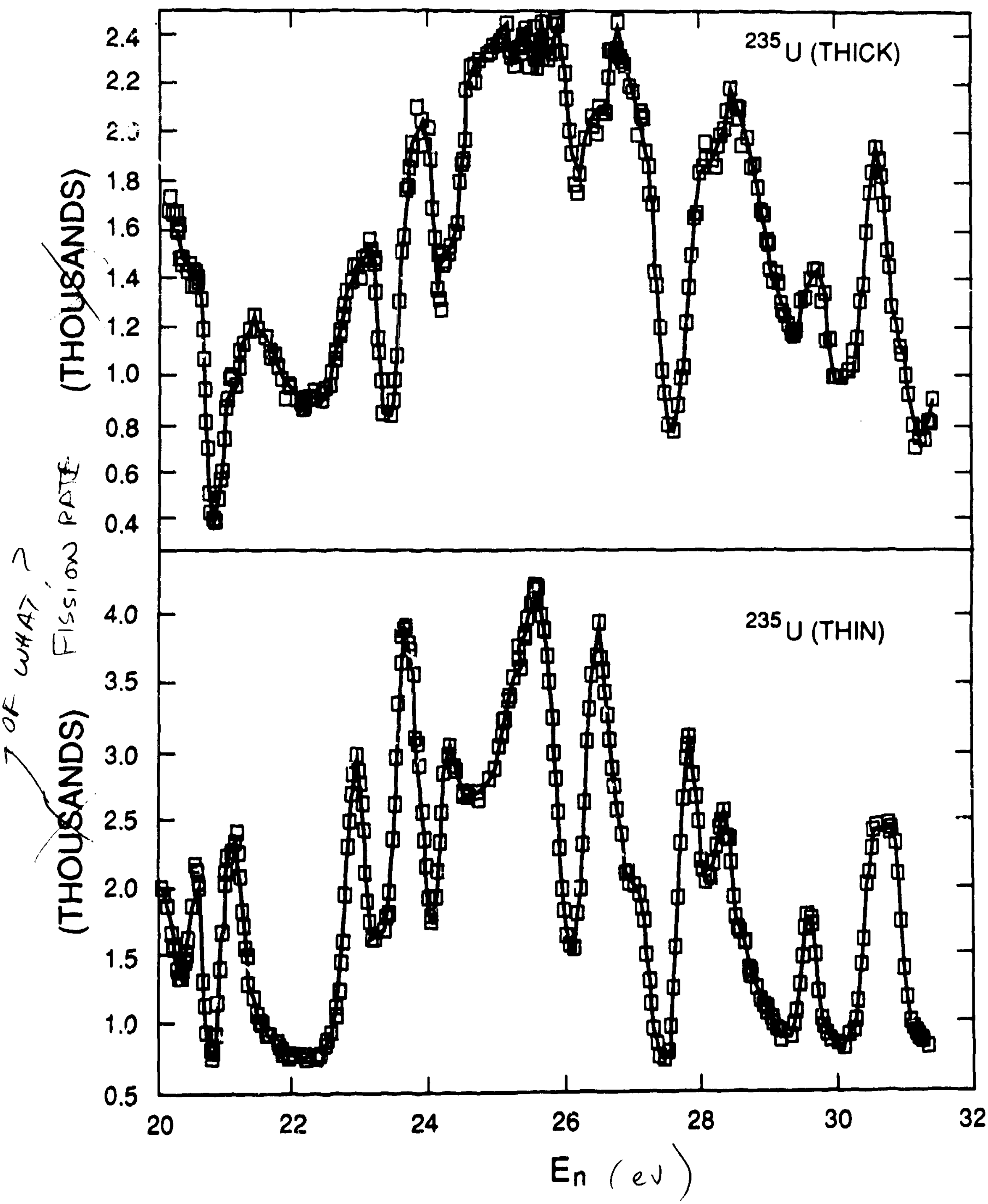
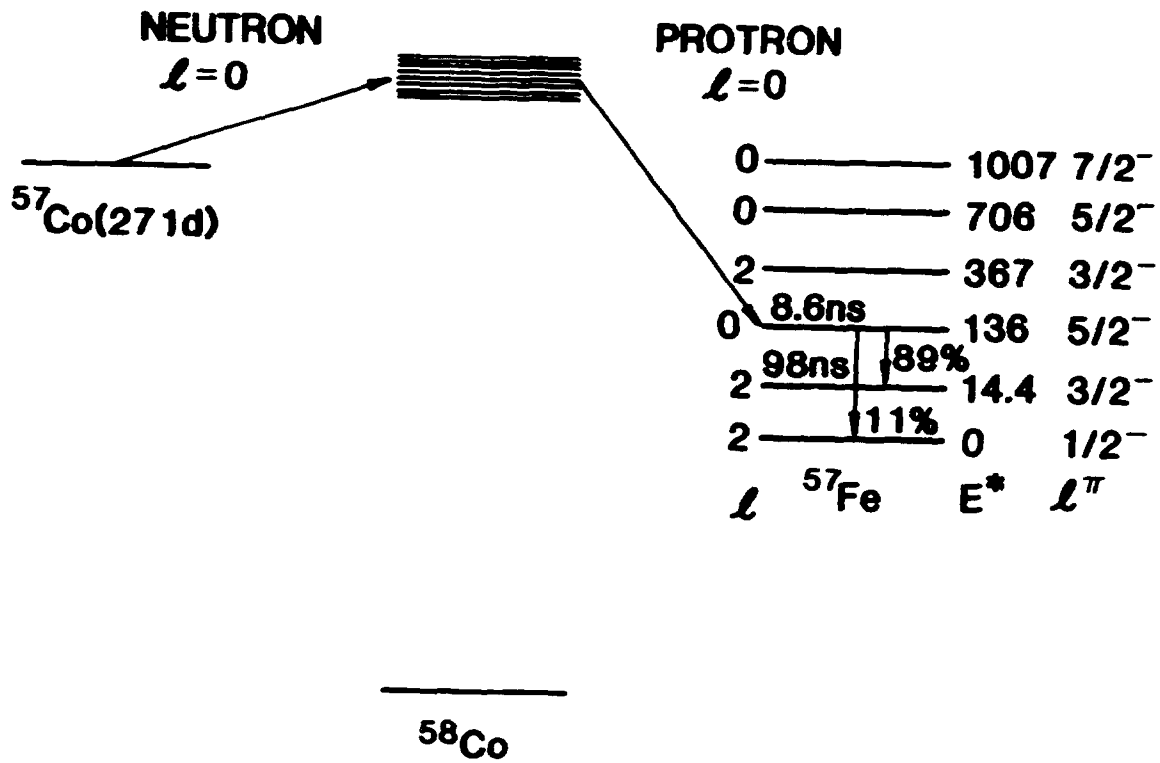


Fig.

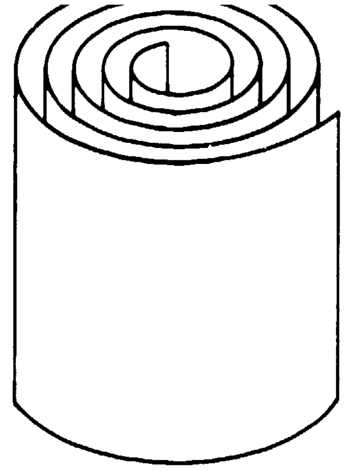


^{235}U (THICK)
^{235}U (THIN)
(THOUSANDS)
(THOUSANDS)
FISSION RATE
? OF WHAT ?
2.4
2.2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
20
22
24
26
28
30
32
En (eV)

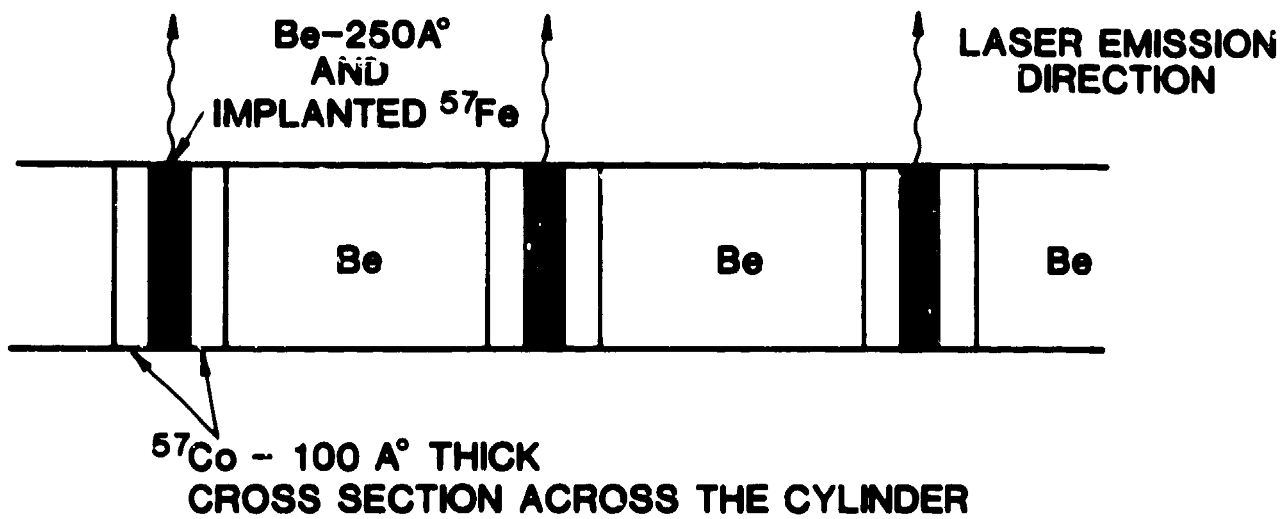


NEUTRON
ℓ=0
PROTRON
ℓ=0
57Co(271d)
0 1007 7/2⁻
0 706 5/2⁻
2 367 3/2⁻
8.6ns
0 136 5/2⁻
98ns
89%
2 14.4 3/2⁻
11%
2 0 1/2⁻
ℓ 57Fe E* ℓπ
58Co

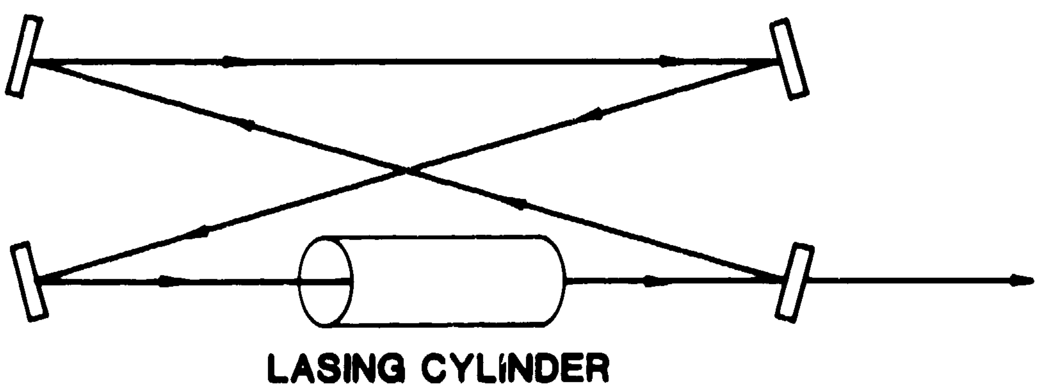
Fig 8



(a)


Be-250A°
AND
IMPLANTED ^{57}Fe
LASER EMISSION
DIRECTION
Be
Be
Be
^{57}Co - 100 A° THICK
CROSS SECTION ACROSS THE CYLINDER

(b)


LASING CYLINDER

(c)

Fig 9

SPALLATION NEUTRON SOURCE INTENSITIES